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TRAFFICABILITY OF SOIL AS RELATED TO MOBILITY OF VEHICLES

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SOIL MECHANICS AND FOUNDATIONS
DIVISION

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TRAFFICABILITY OF SOIL AS RELATED TO MOBILITY OF VEHICLES

R. C. Stewart and S. J. Weiss

INTRODUCTION

The vehicle-mobility research conducted by the U. S. Naval Civil Engineering Research and Evaluation Laboratory has arisen through the need of the Naval Construction Battalions to move material and to carry on operations in the widest possible ranges of weather and terrain. One goal towards which all work has been directed is the development of an analytical method of estimating vehicle performance that will preclude the necessity of conducting extensive "go" and "no go" tests for every specific military vehicle.

The ability to determine vehicle performance analytically has great tactical significance. Performance charts for any vehicle can be precomputed, and the movement of trains of vehicles can be intelligently planned. A satisfactory vehicle-mobility analysis also enables the setting up of criteria whereby vehicles may be designed on a rational rather than an empirical basis. The meeting of design specifications may be accomplished without extensive alteration and modification of the finished vehicle.

Mechanical Properties of Soil

Radically Simplified Concept of Soil

Practically every theory in applied mechanics is based on a set of assumptions concerning the mechanical properties of the materials involved. These assumptions are always to a certain extent at variance with reality. Soil mechanics actually deals with a completely fictitious material, for the theories of behavior of soils under stress are based upon radically simplifying assumptions of the characteristics of this complex medium.[1] The application of soil mechanics to military vehicle-mobility problems has required still greater simplification and approximations in order to obtain an all-embracing concept that may be applied to varying terrain under all weather conditions.

Thus for the purpose of estimating the performance of vehicles, soil is completely classified by three properties alone:

1. Density
2. Apparent cohesion
3. Apparent internal friction

The last two of these properties are by far the most important for they characterize the shearing strength of the soil which directly influences the tractive effort that a vehicle can develop therein.

Shearing Strength of Soil

The empirical relationship between the normal stress on every section through a mass of cohesive soil and the corresponding shearing resistance

per unit of area s was developed nearly two hundred years ago and is known as Coulomb's Empirical law.[2]

This empirical equation

$$s = \sigma \tan \phi + c \qquad (1)$$

where c = coefficient of apparent cohesion, psi

and ϕ = apparent angle of internal friction, degrees

can be represented graphically as a straight line (Figure 1) whose slope is tan ϕ and whose intercept with the Y axis is equal to c.

The values c and ϕ contained in the preceding equation can be determined by means of laboratory tests, by measuring the shearing resistance on plane sections through the soil at different values of the normal stress σ. The simplest, oldest, and most common method for this investigation is known as the direct-shear test. It is performed by means of the box-shear or direct-shear apparatus illustrated by Figure 2. The apparatus consists of a lower frame that is stationary and an upper one that can be moved in a horizontal direction. The shearing force is applied by pulling the upper frame of the shear box, causing the soil sample to shear along the boundary plane between the upper and lower frame.

Action of Soil Beneath Vehicle Track

For precise laboratory work, the box-shear apparatus has several inherent disadvantages. Foremost among these are:

1. Change in area of the surface of sliding as the test progresses.
2. Unequal distribution of the shearing stresses over the potential surface of sliding.
3. The rapidity with which the water content of saturated samples of many types of soil changes as a result of a change in stress.

Owing to these inherent disadvantages, the simple box-shear apparatus has been modified and supplemented by other laboratory soil-testing apparatus. However, the similarity of the action of the box-shear apparatus to the action of a vehicle track in soil is too striking for this simple test procedure to be discarded when a design was being studied for a field instrument capable of classifying the trafficability (the ability to allow the passage of vehicles) of soil.

The similarity in action between a portion of a vehicle track and the direct-shear apparatus is shown in Figure 3. In the nomenclature adapted for vehicle-mobility studies, the total shearing resistance is called tractive effort, H, and the relationship between vehicle loading, V, and tractive effort, neglecting lateral flow effects is

$$H = V \tan \phi + cA, \qquad (2)$$

where A is the area of track contact.

This equation is identically Coulomb's Empirical Law, substituting total loads in place of unit stresses.

The Soil Truss[3]

The direct-shear apparatus that has been developed at the Naval Civil Engineering Laboratory for field determination of c and ϕ is shown in Figure 4.

It is called the "soil truss" and consists essentially of two legs:

1. An active leg to which is attached a frame and anvil, the function of which is identical to that of the upper frame and anvil of the direct-shear apparatus.

2. An anchor leg, to which is attached a spade to provide stability and support for the instrument.

The ground itself is the counterpart of the lower frame of the direct-shear apparatus. The spade is designed to remain fixed in the ground while the active leg shears a prism of soil entrapped in the frame under the anvil, the soil being cleared from the front and sides to eliminate the resistance of soil outside the frame.

The force required to shear the soil is produced as a vertical effort by the operator. This vertical effort produces both normal and shearing stresses upon the entrapped prism of soil, the ratio of the two stresses being dependent upon the leg angle to which the truss initially is set.

Plotting of the data is facilitated by the use of a special chart, as shown in Figure 5, whereby vertical force and protractor readings are plotted directly without the necessity of converting the data to normal and shearing stresses. Operation of the soil truss at various leg angles enables the plotting of Coulomb's Empirical Equation for the soil from which the two characteristics, c and ϕ, may be determined.

Vehicle Performance

Vehicle Performance Equations

All military vehicles for mobility purposes fall into one of the following categories:

1. Self-propelled vehicles
2. Prime movers
3. Trailers

A self propelled vehicle need perform no other function than to power itself over the terrain. A prime mover must be able to pull or push a load in addition to moving itself. A trailer cannot move unless towed or pushed by a prime mover.

The resistance to towing developed by a trailer is called rolling resistance and is denoted by R.

The pull a prime mover must exert in addition to moving itself is denoted by F.

Thus, a self-propelled vehicle need develop only enough tractive effort to overcome its rolling resistance, or

$$H = R. \qquad (3)$$

A prime mover must develop enough tractive effort to overcome its own rolling resistance and to provide a drawbar pull sufficient to pull its load, or

$$H = R + F. \qquad (4)$$

The dependence upon c and ϕ of the tractive effort of the vehicle has already been demonstrated. The rolling resistance of the vehicle is also a function of these soil characteristics, although not as simple expressed. An expression for rolling resistance developed at NAVCERELAB is as follows:

$$R = V\sqrt{\frac{z}{D - z}} + R_i, \qquad (5)$$

Where D = outside diameter of curved front of track or wheel,

z = sinkage of vehicle,

R_i = internal rolling resistance, lb (friction losses in track chains and pins, etc.),

and the relationship enabling the computation of sinkage is

$$\frac{mV}{b\left[L + \sqrt{Dz - z^2}\right]} = \frac{\gamma z N_\phi + 2c\sqrt{N_\phi} + \frac{2c}{1 + \tan \phi}}{\tan (45 - \phi)}, \qquad (6)$$

where b = track or wheel width, in.,

z = density of soil, lb per cu in.

$$N_\phi = \tan^2 \left(45 + \frac{\phi}{2}\right)$$

L = distance center drive sprocket to center front idler, in.; for a wheel, L = 0.

m = influence factor, varies between 0.25 and 1.0, depending upon vehicle suspension, grouser height, and whether vehicle is wheeled or tracked.

The Index of Performance

The index of performance of a prime mover is unquestionably the amount of load it can pull in addition to moving itself. Thus the prediction of the performance for a tractor becomes the estimating of the drawbar pull available for pulling a load.

The index of performance of a self-propelled vehicle not used as a prime mover is merely whether or not passage of terrain is possible, a strictly "go" or "no go" affair. This would correspond to a prime mover being able to move itself but not being required to pull a load. Thus if the vehicle is analyzed in the same manner as a tractor and the predicted drawbar pull is anything above zero, capacity to pass over the terrain is indicated.

The index of performance of towed vehicle is the load a prime mover would have to exert as drawbar pull in order to move the vehicle. This load is the sum of the internal and external rolling resistance of the towed vehicle.

The predicting of vehicle performance then becomes:

1. For a prime mover or self-propelled vehicle, the estimating or drawbar pull.
2. For a towed vehicle, the estimating of total resistance.

The prediction of drawbar pull for a prime mover first requires a mathematical expression for this force. The law of conservation of energy dictates that:

Power supplied to sprocket of track	=	Power expended in moving soil through slippage	+	Power expended in pulling load	+	Power expended in moving vehicle against its own resistance

or

$$550P = H(1-k)v + Fkv + Rkv \qquad (7)$$

Where k = slip factor; $k = 1$ (no slippage); $k = 0$ (100% slip)

P = available engine horsepower

v = peripheral velocity of wheel or track, fps

The limitations imposed by the soil are

$$H = F + R \qquad (4)$$

since the summation of all horizontal forces must equal zero in order for the vehicles to move at constant speed. Solving equations 4 and 7 simultaneously gives

$$\frac{550P}{v} = F + R = H \qquad (8)$$

since F is the index of performance of the vehicle, equation 8 will be expressed as

$$\frac{550P}{v} - R = F = H - R \qquad (9)$$

Maximum $(\frac{550P}{v} - R)$ is indicated in vehicle specifications as the maximum calculated drawbar pull in low gear at overload. For the Caterpillar Diesel D-4 tractor this value is 10,600 lbs.[4]
Thus

$$10,600 = F \geq H - R \qquad (10)$$

which demonstrates that there are two practical limiting conditions of operation of this prime mover:

1. When the drawbar pull = 10,600 lbs. (The tractor is pulling the maximum load allowed by its engine.)

2. When the drawbar pull = H - R. (The tractor is pulling the maximum load allowed by the soil.)

The actual limiting condition of operation will be whichever is the lesser of these two.

Study of equation 10 indicates that the tractive effort, H, for the Caterpillar Diesel D-4 can never exceed 10,600 lbs despite the capabilities of the soil owing to the power limitations imposed by the tractor's engine.

Tractive Effort

The work of the Canadian Directorate of Vehicles and the Aberdeen Proving Ground has resulted in devising the following formula for the prediction of tractive effort of a conventional closed-link track:[5]

$$H = V \quad [(1 + F_h)\tan\phi + F_h F_s \tan^2\phi] + 2cL(b + 2h) \qquad (11)$$

where

F_h = factor dependent on depth-width ratio of grousers

F_s = factor dependent on spacing-width ratio of grousers

h = depth of grouser - in

This equation has been closely corroborated by experiment.

Drawbar Pull

Drawbar pull, or the effort a prime mover can exert in addition to moving itself is the difference between tractive effort and rolling resistance. Rolling resistance is the sum of the internal and external rolling resistance. Tractive effort can be expressed quantitatively by equation 11. Rolling resistance can be estimated quantitatively by equation 5. Thus a procedure is now set up to predict drawbar pull for any (c,ϕ) soil condition.

Vehicle Performance Charts

One advantage of this analytical treatment of the vehicle-mobility problem is the ability to precompute for all ranges of the variables and set up the results in the form of charts for ready reference. Figures 6 and 7 are samples of such performance charts for a prime mover and a trailer respectively. First-hand knowledge of the soil characteristics obtained through scouting parties equipped with instruments such as the soil truss will enable rapid determination of the suitability of the terrain for passage of these vehicles, for an overlay of these two charts gives instantaneous knowledge of the advisability of their coupling.

Experimental Verification

For purposes of economy and control, the major portion of the experimental work to date has been performed in the laboratory upon small-scale models rather than in the field upon full-sized vehicles. Special equipment has been developed for this purpose. Figure 8 shows the traction test apparatus that allows selection of vehicle loading and slippage and continuous recording of input torque, drawbar pull, and sinkage. Figure 9 shows a sample instrument record. Close correlation has been obtained between the experimental and analytical results in the several phases of the program already completed. Limited field testing of full-size tractors has demonstrated the ability to extend this correlation to the full-sized vehicle.

Limitations of the Analysis

The Rolling Resistance Chart of a towed vehicle and the Drawbar Pull Chart of a prime mover provide a basis for tactical prediction of vehicle movement over level ground. An overlay of these two charts gives instantaneous knowledge of the suitability of the two vehicles for coupling in any (c,ϕ) soil condition.

As yet this procedure has been checked experimentally only by quantitative verification of a few of the basic components and full scale tests in a limited variety of soils. However, the results show a marked qualitative conformance with observation and practical experience in the field.

In the development of the equations, many of the soil properties affecting performance have been neglected or have had their contribution explained by their effect upon cohesion or angle of friction. The compressibility of soil has been completely neglected. An abrupt change in stress condition is implied below the edge of the track or wheel. The bearing pressures calculated are independent of the size and shape of the track or wheel. All these are known to be contrary to the facts and will provide a starting point for refinement of the analysis.

Conclusions

As a result of the investigation herein presented, the following conclusions are presented:

1. Despite the fictitiousness of the classical concept of soil, the angle of internal friction and the coefficient of cohesion appear to remain the key to the prediction of vehicle performance.

2. Utilizing an effective angle of friction, $\emptyset$, and an effective coefficient of cohesion, c, determined on the spot, eliminates much of the error associated with considering them constants of the soil.

3. Using the effective angle of friction, $\emptyset$, and an effective coefficient of cohesion, c, as coordinates, Drawbar-Pull Charts can be prepared in advance for every self-propelled vehicle in a tactical organization. Rolling Resistance Charts can be similarly prepared for every towed vehicle.

4. Upon determination of the effective $\emptyset$ and the effective c of doubtful soil, determined on the spot, utilizing field instruments, such as the Soil Truss developed for this purpose, the performance of either individual vehicles or trains of vehicles can be predicted and movement of the tactical organizations can be planned accordinaly.

References

1. Terzaghi, Karl; Theoretical Soil Mechanics; John Wiley and Sons, Inc., 1943.

2. Taylor, Donald W.; Fundamentals of Soil Mechanics; John Wiley and Sons, Inc., 1948.

3. U. S. Naval Civil Engineering Research and Evaluation Laboratory; Technical Memorandum M-003, Preliminary Study of Vehicle Mobility as Related to the Traffic-ability of Tractor Media; by R. C. Stewart and S. J. Weiss, 31 October 1950.

4. Caterpillar Tractor Co.; Specifications Form 1823-50R.

5. Aberdeen Proving Ground; Effect of Grouser Height on the Tractive Effort of a Vehicle, third Report on Project TT1-698, n.d.

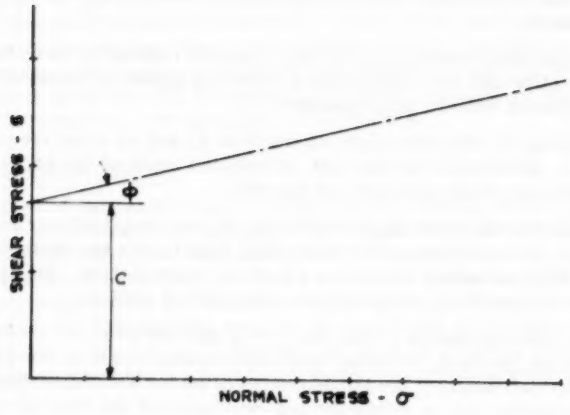


Figure 1

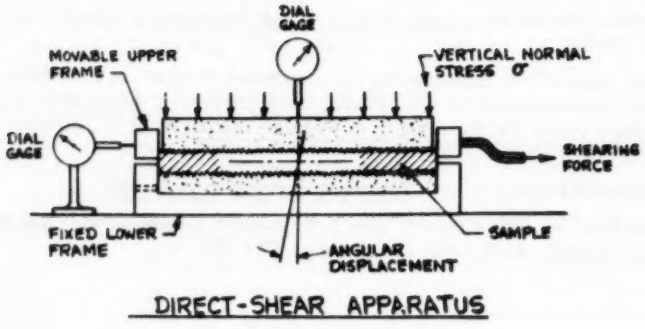
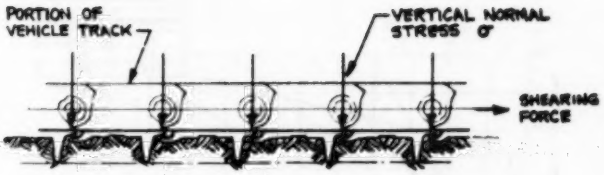


Figure 2



VEHICLE TRACK SHEAR

Figure 3

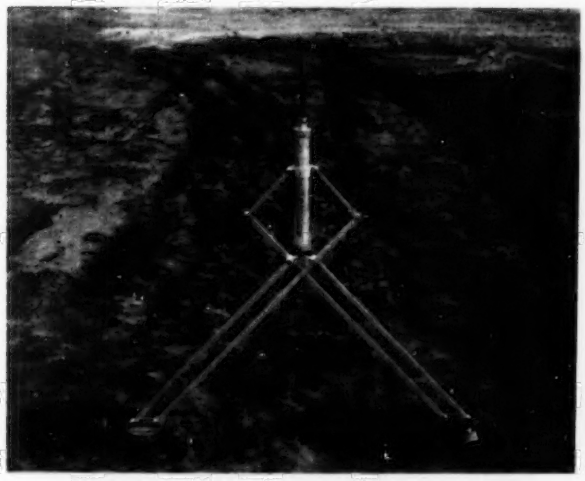


Figure 4. Soil truss mark 2.

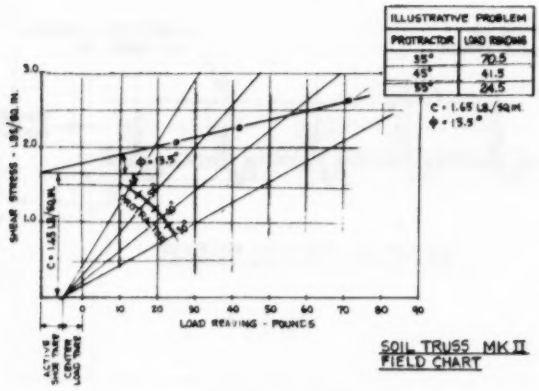


Figure 5

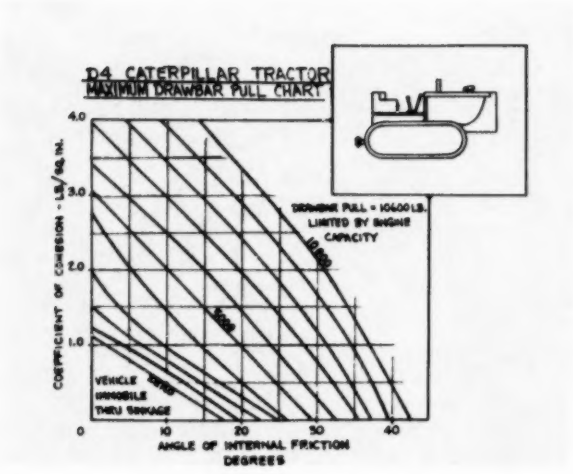


Figure 6

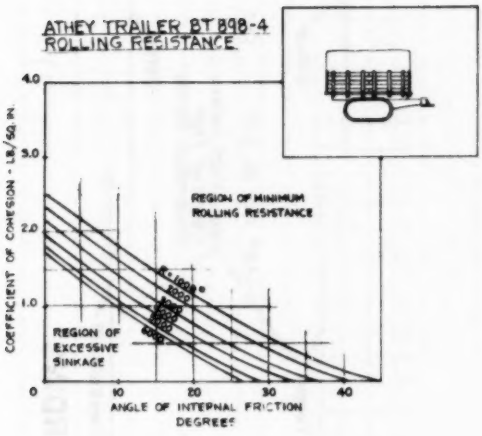


Figure 7

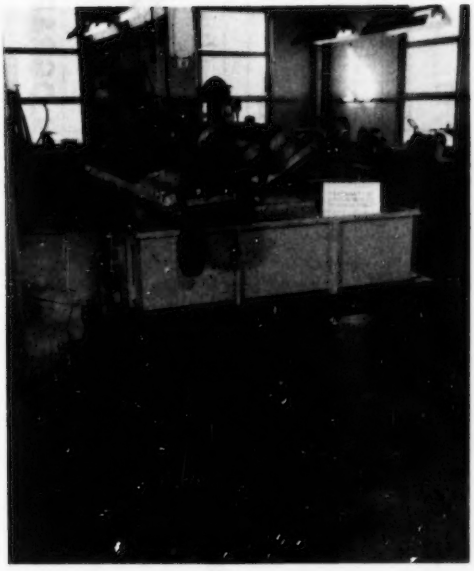


Figure 8. General view of sand test apparatus.

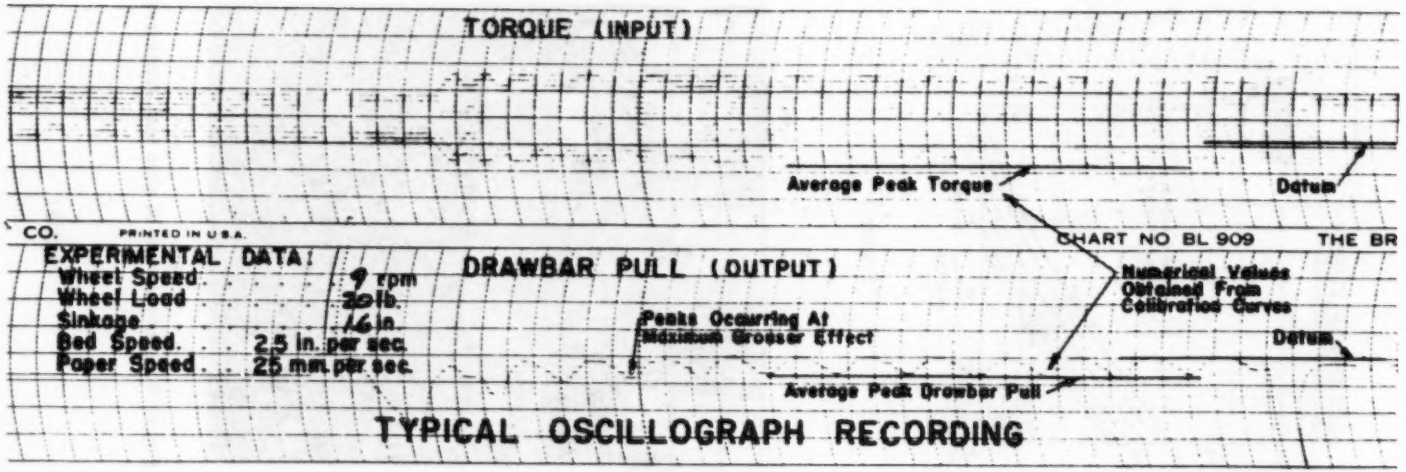

TORQUE (INPUT)
Average Peak Torque
Datum
CO.
PRINTED IN U.S.A.
CHART NO BL 909
THE BR
EXPERIMENTAL DATA:
Wheel Speed . . . . 9 rpm
Wheel Load . . . . 20 lb.
Sinkage . . . . 1.6 in.
Bed Speed . . . 2.5 in. per sec.
Paper Speed . . . 25 mm. per sec.
DRAWBAR PULL (OUTPUT)
Numerical Values Obtained From Calibration Curves
Peaks Occurring At Maximum Grouser Effect
Datum
Average Peak Drawbar Pull
TYPICAL OSCILLOGRAPH RECORDING

Figure 9